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ORIGINAL ARTICLE

Evaluation of Candidate Thermal Protection System Materials for Indian Manned Mission Gaganyaan in Plasma Wind Tunnel Facility

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Abstract

During atmospheric reentry of a manned crew module, the vehicle experiences severe thermal environments due to aerodynamic heating. Protection of crew module necessitates thermal protection systems (TPS) which shield the vehicle structure from the extreme thermal environments. Ground based testing in Plasma Wind Tunnels play a vital role in selection and qualification of TPS for re-entry missions. Three candidate TPS materials identified for the Gaganyaan mission of ISRO are evaluated in Plasma Wind Tunnel facility under simulated reentry environments. Tests are conducted at expected peak heat flux and total heat load conditions and performance of materials are compared based on thermal response and material surface recession characteristics.

Keywords Ablative TPS · Reentry · Plasma Wind Tunnel

Introduction

ISRO is embarking on its first manned mission Gaganyaan and the objective of the mission is to take a crew of three to Low Earth Orbit, do scientific experiments and return them safely to earth. One of the most challenging phases of this mission is the reentry of the crew module into earth atmosphere during which the vehicle experiences severe thermal environments due to aerodynamic heating. The protection of crew module relies on thermal protection systems (TPS) which shield the vehicle structure from extreme thermal environments.

Selection of TPS for a re-entry mission is a challenging task due to the conflicting requirements of inert mass, acceptable erosion/shape change and back wall temperature constraints. Ground based testing under simulated re-entry aerothermal environments is essential for preliminary screening and characterisation of TPS for a specific mission requirement. This can be performed only in Plasma Wind Tunnels wherein high enthalpy environments as experienced during re-entry can be simulated for long durations which is necessary to characterise TPS materials (Park 1990; Grinstead et al. 2005). World over, numerous arc heated facilities of different types and power levels are established for the purpose of evaluation of TPS materials and their details are summarized in Smith et al. (1998).

ISRO has established 6 MW power rated Plasma Wind Tunnel at Vikram Sarabhai Space Centre, Thiruvananthapuram to cater to the requirements of screening, testing and qualification of TPS for re-entry application. This paper summarises the details of screening tests carried out on three candidate TPS materials namely, Carbon Phenolic (CP) composite, Silica Phenolic (SP) composite and Medium density Silica Phenolic (MDSP), identified for Gaganyaan mission based on the preliminary mission requirements.

Ground Simulation of Reentry Environments

During reentry, the vehicle experiences wide range of flow velocities, stagnation pressure and surface heat flux. Simultaneous replication of all flight environments is not possible in any single ground test facility (Sharma et al. 1996). From the point of testing of TPS, it is necessary to replicate the flight heat flux levels for duration of actual reentry to qualify the material (Prabhu et al. 2009). For Gaganyaan mission, the preliminary design is

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under progress and the typical predicted heat flux profile is shown in Fig. 1. The forward region is subjected to a peak heat flux of around 150 W/cm^2 and total heat load of 26.8 kJ/cm^2.

For system level testing of reentry TPS, Plasma Wind Tunnel facility was commissioned in 2011 at Vikram Sarabhai Space Centre, ISRO. The facility is capable of simulating flight heat flux levels on scaled down models. The heart of the facility is a 6 MW power rated segmented arc heater capable of generating stagnation enthalpy in the range of 10–30 MJ/kg. The high enthalpy arc heated gas is then expanded through a segmented C–D nozzle to generate a high velocity free-jet in the test section. The test section can accommodate axi-symmetric stagnation models upto ϕ 150 mm and wedge type panel models of size 150 mm × 150 mm. Further the free-jet is captured and decelerated by the diffuser system, cooled in an after cooler and subsequently discharged into the vacuum vessels. The photograph of the facility is shown in Fig. 2. The overall simulation capabilities of PWT Facility is summarised in Table 1.

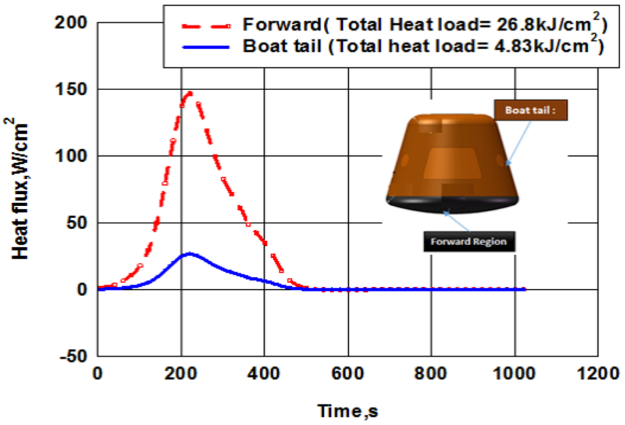


Fig. 1 Gaganyaan mission heating conditions Estimation (Varghese 2019)

Table 1 Overall capabilities of PWT

S. no.	Parameter	Value
1	Operating power	upto 6.0 MW
2	Arc heater pressure	upto 4 bar
3	Arc heater throat	26 mm
4	Nozzle area ratio	30, 75, 150, 200
5	Stagnation enthalpy	10–30 MJ/kg
6	Model size	upto ϕ 150 mm
7	Model stagnation pressure	3–20 kPa

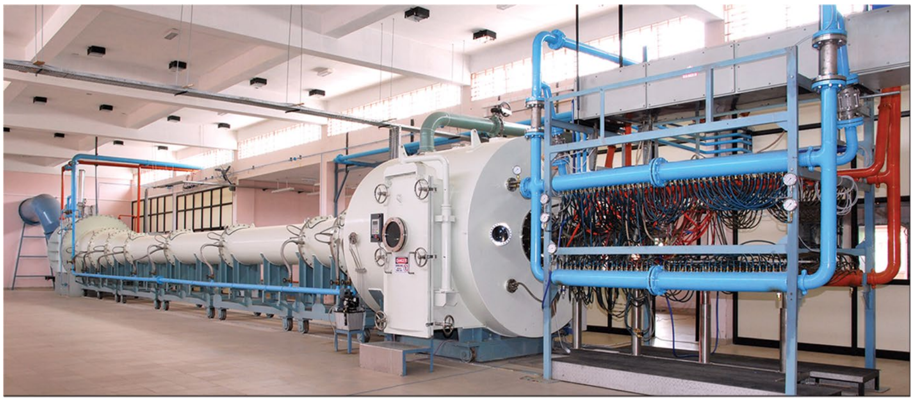
Ablative TPS for Reentry

The fore-body region of almost all manned crew modules flown till date uses ablative TPS. The reasons for choosing ablative TPS is because it is simple, reliable, self-regulating and has proven flight heritage. The details of ablative TPS used in various NASA and ESA missions are described in Laub and Venkatapathy (2004) and Bouilly et al. (2006), respectively. Within the class of ablative TPS, the choice of a particular material depends on the peak heat flux estimated for the mission and the required TPS thickness is determined by the total heat load (Prabhu et al. 2009). Other factors that decide the choice of TPS materials are the maturity of manufacturing process, performance in simulation tests and overall available TPS mass budget. For the Gaganyaan mission, comparative study of three candidate forward heat shield materials are proposed namely carbon phenolic (CP), silica phenolic (SP) and a newly developed medium density silica phenolic (MDSP).

Candidate TPS Materials for Gaganyaan

a. Carbon Phenolic–(CP): This is a heritage material for ISRO used in orbital recovery mission, Space capsule Recovery Experiment (SRE) and Crew module Atmospheric Re-entry Experiment (CARE) sub-orbital mission.

Fig. 2 Plasma wind tunnel facility, VSSC/ISRO



This material is also used as liner material in high heat flux regions of solid rocket motor nozzles. It is manufactured through compression molding of carbon phenolic prepreg chops of size 15 mm × 15 mm under a pressure of 150 bar and temperature of 150 °C. The prepreg is made from rayon-based carbon fabric. Carbon phenolic with random fiber orientation has density of 1.4 g/cc with room temperature conductivity of 0.8 W/mK. This material is best suited for use in high heat flux environments, typical to ballistic re-entries, due to its superior erosion resistance.

b. Silica Phenolic–(SP): The manufacturing process for Silica Phenolic is similar to that of random fiber carbon phenolic wherein silica phenolic prepreg chops made from high silica fabric is used instead of carbon phenolic prepreg chops. This material also has heritage in ISRO's mission as it used as liners in low heat flux regions of solid motor nozzles. SP has a density of 1.6 g/cc and room temperature thermal conductivity of 0.40 W/mK.

c. Medium density silica phenolic (MDSP): Towards the efforts for realizing ablative TPS with lower densities, developments are initiated towards lowering the density of Silica Phenolic material with addition of low density filler materials. The newly developed TPS, termed Medium Density Silica Phenolic or MDSP incorporates glass micro-balloons as fillers. This material is manufactured through the compression molding of silica fabric, phenolic resin and glass microballoons under a pressure of 10 bar and at 150 °C. This material is designed for a target density of 1.15 g/cc with room temperature thermal conductivity of 0.2 W/mK. Reduction in thermal conductivity combined with the lower density is expected to reduce the overall mass of thermal protection system when compared to carbon phenolic and silica phenolic materials. However, being a new material, its performance with respect to erosion resistance and thermal response is yet to be evaluated in a ground simulation tests.

Test Scheme

The objective of the present test series is a comparative evaluation of the three candidate TPS materials namely CP, SP and MDSP, identified for use in the forward region of Gaganyaan crew module under simulated reentry environments in PWT facility. Tests are proposed to be carried out at the expected peak heat flux levels and test duration is arrived at to simulate the total heat load. The model configuration selected for the present test series is an axi-symmetric blunt model, with iso-q profile of base diameter 65 mm. The iso-q profile has a nose radius twice the base radius and this profile is chosen as it ensures a near uniform heat flux on the front face (Prabhu et al. 2009).

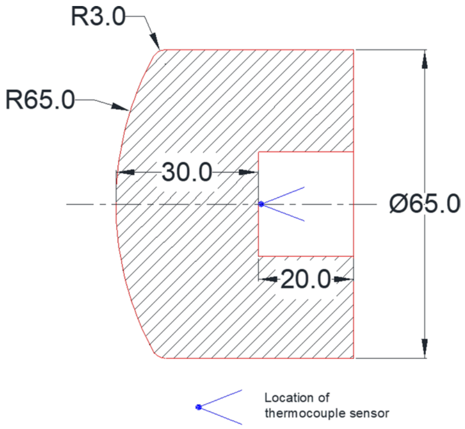


Fig. 3 Schematic of test model configuration

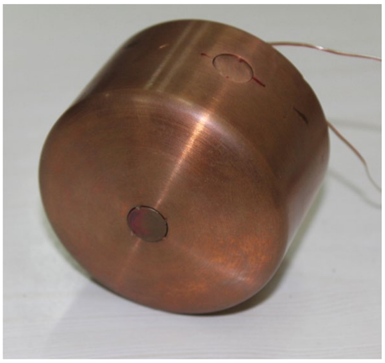


Fig. 4 Photograph of iso-q calibration model

Test model is instrumented with a Type-K thermocouple sensor at the back wall and infrared pyrometer is used to measure the surface temperature at the stagnation region. Figure 3 shows the schematic of model configuration and the instrumentation scheme.

Prior to model testing, the tunnel is calibrated by performing heat flux measurements at the required tunnel operating conditions using an un-cooled copper calibration model. The calibration model is of same geometry as the test model and incorporates slug type heat flux sensors at stagnation region and cylindrical region as shown in Fig. 4. Heat flux is computed from the thermal response of slug sensor as per ASTM standard E-457 (ASTM 2015). Measured cold-wall heat flux (non-catalytic) at stagnation region was calibrated to the required heat flux of 150 W/cm^2 with and uncertainty of ±10 %. This test condition was obtained at an arc heater stagnation enthalpy of 22 MJ/kg and model stagnation pressure of 8000 Pa.

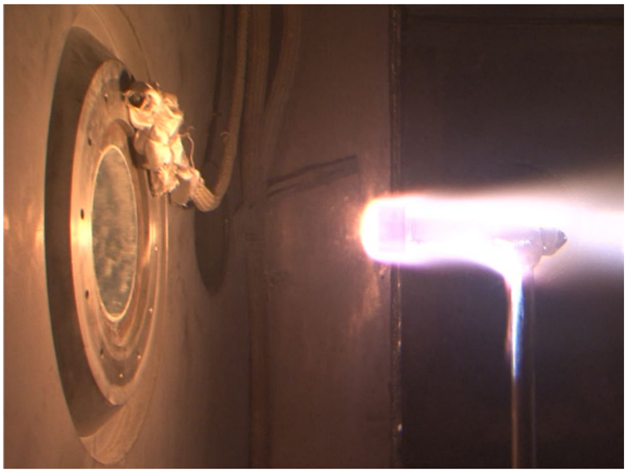


Fig. 5 Photograph of a typical TPS model test in PWT

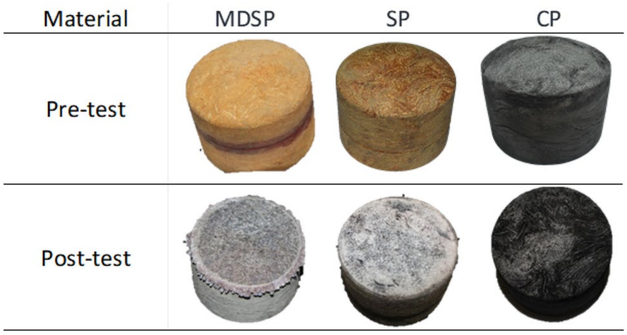


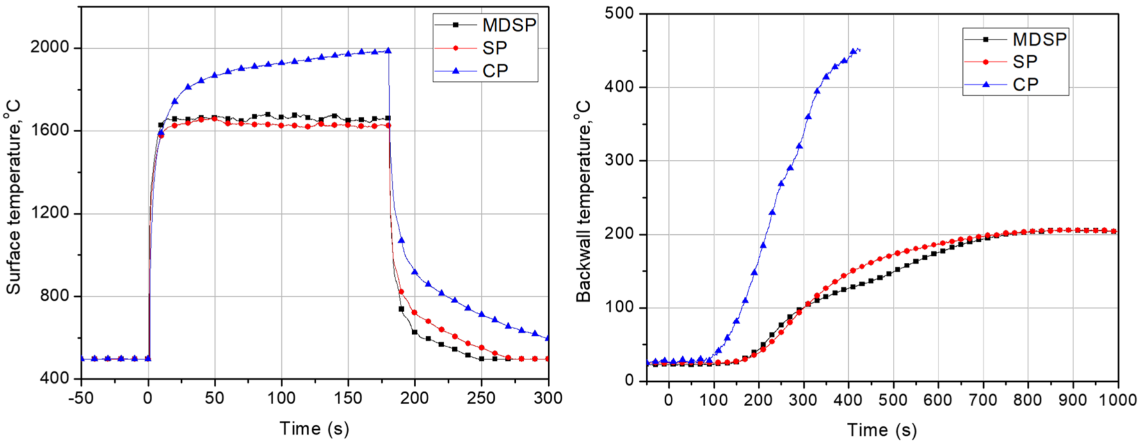
Fig. 6 Pre-test and post-test photographs of TPS materials

Results and Discussions

All three TPS materials (two models each) were tested at a cold wall heat flux of 150 W/cm^2 for duration of 180 s. The photograph of a typical model test in PWT is shown in Fig. 5.

Figure 6 shows the photographs of the test models before and after test. Post-test, the test model surface was profiled to obtain material surface recession. CP has the lowest surface recession at 1.8 mm followed by SP and MDSP respectively. The higher surface recession of MDSP is due to the melting of glass micro-balloon fillers. The re-crystallization of molten glass micro-balloons at the model corners is visible in the post-test photograph in Fig. 6. The test specimens are sectioned diametrically to evaluate the char depths. The maximum surface recession and the char depth values for all TPS materials are summarized in Table 2. It can be seen that MDSP has the lowest char depth

Surface temperature at stagnation region and back-wall temperature measured during test is shown in Fig. 7a, b, respectively. The data plotted is averaged data of two tests. The surface temperature stabilises at around 1600 °C for both SP and MDSP TPS. which is attributed to the melting phase change of the silica fibers. For CP, the surface temperature is seen to rise till 2000 °C since carbon sublimes only at temperature close to 4000 K. The back-wall temperature rise for CP is higher than both SP and MDSP due to its higher thermal conductivity. For SP and MDSP, the combined effects of thermal conductivity and surface ablation results in nearly identical trend with respect to back-wall thermal response.



(a) Surface temperature

(b) Back-wall temperature

Fig. 7 Comparison of surface and back-wall thermal response data of TPS materials

Table 2 Surface recession and char depth

Material	Max. surface recession (mm)	Char depth (mm)
CP	1.8	30.0
SP	2.5	9.5
MDSP	7.3	7.8

Conclusion and Future Work

The comparative evaluation of three candidate TPS materials for Gaganyaan forward region heat shield is performed in Plasma Wind Tunnel Facility. Tests were conducted at peak heat flux and total heat load conditions expected for the mission. It can be seen that MDSP and SP has comparable back-wall temperature rise. Since MDSP has a lower density, this translates to a lower overall TPS weight which gives MDSP an edge over SP TPS. However surface recession of MDSP being highest, the effect of overall shape change on the aerodynamic configuration of a vehicle is to be studied in detail. Efforts are now initiated towards improvements to MDSP by replacing glass micro-balloon filler with silica aerogel filler. Further, a new graded TPS development is also initiated which envisages to combine the benefits of erosion resistance of SP with the reduced thermal conductivity and density of the MDSP variant.

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